HARVEY W. KO, JUDITH A. GIANNINI, and PATRICIA J. HERCHENROEDER

OCEANOGRAPHIC ELF ELECTROMAGNETIC INVESTIGATIONS AT APL

An extensive program to investigate the nature of extremely low frequency (ELF) electromagnetic wave propagation in the ocean environment has resulted in a continuing series of oceanographic measurements by APL, which has fabricated a hydrodynamically stable, calibrated source that is towed underwater and a three-axis underwater detector loop to support the program. Unique subsurface-to-subsurface measurements using the instruments agreed with theory to within the experimental uncertainty of 20%. An array of triaxial superconducting magnetometers was used as a long-baseline gradiometer to make above-surface propagation measurements. Unique geomagnetic noise measurements in the ELF band, yielding broadband noise reduction, were also made.

INTRODUCTION

Since 1974, an effort has been made at APL to determine the characteristics of man-made and natural ELF electromagnetic waves in the 3 hertz (Hz) to several kHz range in the ocean environment. This work is believed to be unique and complements other programs in the United States by providing sophisticated measurement techniques useful in a complex ocean environment. Until the advent of the APL program, oceanographic ELF electromagnetic data were scarce.

Historically, the practical use of man-made, low-frequency electromagnetic waves without wires can be traced back to 1899 when Nikola Tesla envisioned a worldwide communications network using a huge spark-gap transmitter to set the earth itself into a resonant mode near 10 Hz.[1] In 1901, Marconi successfully demonstrated spark-gap transatlantic signal transmission at near-DC frequencies. About 1920, Schlumberger proved the feasibility of transmitting waves near 100 Hz without wires to useful distances in France. For the next 50 years, increased interest in wireless transmission led to developments in the application of electromagnetic waves in the ELF range to electrical geophysical prospecting. The conductivity of crustal layers and the location of ore deposits are readily determined using ELF methods, from either surface or airborne transmitters, because of the improved penetration of energy (i.e., small skin-depth attenuation) into conducting media at low frequency. Also, because the wavelength of the signals is large (wavelength, λ, is 300 kilometers at a frequency, f, of 1 kHz in air), the fine-scale structure of the medium does not seriously affect the interpretation of the signals. Another area of increased investigation has been the use of ELF electromagnetic waves in communications.

A multifaceted approach based on theoretical formulation, instrumentation fabrication, and experimental data collection and analysis is followed in the program at APL. The work has concentrated on the quasi-static range (much less than one free-space wavelength). Signal falloff rate, polarization, and the influence of the ocean's stratification and bottom on the character of ELF electromagnetic waves are some of the issues emphasized. Simultaneous measurements characterizing the geomagnetic noise down to the $10^{-5} \gamma/\sqrt{Hz}$ level [1 gamma (γ) $= 10^{-9}$ tesla $= 10^{-5}$ gauss] with several triaxial superconducting magnetometers is another unique aspect of the APL program. Since the earth's ambient static magnetic field is about $10^4 \gamma$, electromagnetic measurements of one part in 10^9 in the ocean environment would be impossible were it not for the collaboration of the Submarine Technology, Space Development, Strategic Systems, and Engineering Facilities Departments at APL and over 15 subcontractors elsewhere to bring high technology in ocean engineering, electronics, and signal processing to bear on the problem.

Many towed-body and ELF sensor-package standardization trials were performed off the coast of Ft. Lauderdale, Florida, from 1974 to 1977 with the APL research vessels R/V *Cape* and R/V *Cove*.[2] These trials were required to assess towed-body stability, mechanical integrity, launch and recovery procedures, electronics compatibility, and system durability. Surface and subsurface propagation and geomagnetic noise measurements were conducted in 1975, 1976, 1977, and 1979 off Ft. Lauderdale; Nassau, Bahamas; and St. Croix, U.S. Virgin Islands. The measurements in 1979 were performed using measurement stations in the United States, England, St. Croix, and Antarctica. This article provides some insight into the instrumentation systems, data analy-

sis procedures, and propagation results obtained thus far from this broad-based APL program.

DESCRIPTIONS OF INSTRUMENTATION SYSTEMS

Underwater Calibrated Source

Experimental validation of subsurface-to-air and subsurface-to-subsurface propagation of ELF electromagnetic signals requires known radiating sources of different types. A towed Underwater Calibrated Source was fabricated at APL[3] to provide ELF signals from the ocean depths in a precise well-controlled manner. It consisted of three electromagnetic dipoles—a horizontal magnetic dipole, a horizontal electric dipole, and a vertical magnetic dipole—built into a stabilized platform (see Fig. 1). Any one of the dipoles could be excited with a calibrated alternating current to provide electric field or magnetic field signals. A dummy load that could be activated periodically was also placed on the platform to ensure that the signals received were from the dipoles and not from the Underwater Calibrated Source cable or research vessel. Also included in the package were heading, roll, pitch, and depth sensors for sensing towing characteristics.

The system was designed to be towed by a nonmetallic research vessel that could also provide electronic support. Shipboard electronics included a function generator; current amplifier; digital displays for current, heading, roll, pitch, and depth; attitude sensor recording electronics; attitude sensor power supply; and a range pinger for tracking purposes.

Ham's Bluff Receiving Station

As part of the initial effort in 1975 to measure subsurface-to-air signals from the Underwater Calibrated Source and to measure geomagnetic noise, a three-axis, multiturn receiving coil system was designed and fabricated at APL. A rigid cement structure was built along the northeast coast of St. Croix as permanent housing for the receiving coils. The receiving station was located next to the U.S. Coast Guard Lighthouse near Ham's Bluff at 17°46'N latitude, 64°53'W longitude. The site was approximately 90 meters above mean sea level and was within 137 meters of the water's edge, thereby providing close proximity at significant altitude to the ocean. Three theodolite stations near the receiving station were used with the Atlantic Fleet Weapons Training Facility at St. Croix to provide optical track of moving surface vessels such as those towing the source.

Each coil of the triaxial receiver consists of 1000 turns of bifilar wound wire, wrapped around a circular coil form that is 1.8 meters in diameter. The amplifier-data acquisition and recording system was housed within the lighthouse. Two coils measured the horizontal (X and Y) components of the magnetic field along the directions of 65° or 245° and 155° or 335° from true north. A third coil measured the vertical (Z) component of the magnetic field. That system was atmospheric-noise limited, without the use of any geomagnetic noise reduction techniques, down to the tape noise limit of 10^{-5} $\gamma/\sqrt{Hz}$ at 1 Hz. Since the response of any coil system is proportional to the time rate of change of the magnetic flux linking the coil, that coil system's sensitivity was degraded substantially as the frequency of the signal approached zero.

Triaxial superconducting magnetometers produced by the S.H.E. Corporation of San Diego were also used to measure ELF magnetic fields. Each magnetometer system consisted of three mutually orthogo-
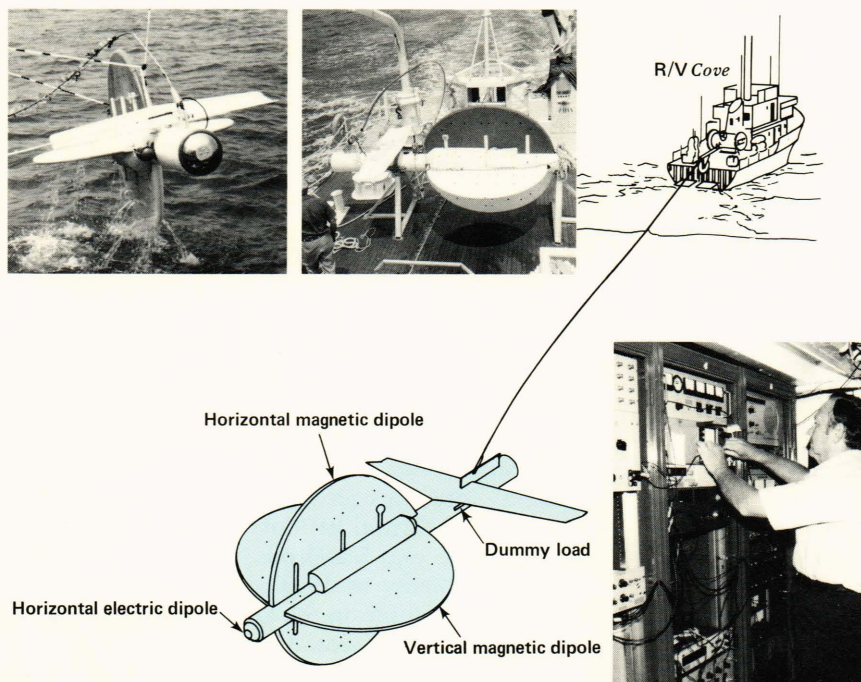

R/V *Cove*

Horizontal magnetic dipole

Dummy load

Horizontal electric dipole

Vertical magnetic dipole

Figure 1 — Underwater Calibrated Source platform towed in stabilized fashion by the nonmagnetic R/V *Cove*. Shown are the three dipoles that furnish calibrated ELF signals for propagation studies.

nal Superconducting Quantum Interference Device (SQUID) sensors that provided measurement of all three Cartesian components of the field, one radio-frequency head for control and signal interrogation, one control unit that contained low-frequency electronics to operate the SQUID system at different sensitivities and bandpass filter settings, and a fiberglass Dewar flask for liquid helium. The sensitivity of such a unit is 10^{-5} $\gamma/\sqrt{Hz}$ with a dynamic range of 134 decibels from 1 to 100 Hz and a linearity of one part per million.

The choice of a superconducting magnetometer over a conventional magnetometer such as one using a coil system is often made for several reasons: (a) it is compact and portable, (b) it has unsurpassed sensitivity to low-frequency signals, (c) it has great dynamic range and fine linearity, and (d) it is a vector device that allows measurement of the components of the field, separately or simultaneously, thereby giving the direction as well as the magnitude of the signal.

Long-Baseline Gradiometer

Periodically since 1976, an array of the triaxial superconducting magnetometers has been implanted onshore at the southwest tip of St. Croix. This location, called Sandy Point (17°41′N, 64°54′W), was chosen as an ELF sensor location because of its low man-made-noise environment, its proximity to St. Croix range tracking, and its near-sea-level altitude. This array, which consists of two or three complete superconducting magnetometer systems, is called a Long-Baseline Gradiometer. As many as six different sites have been selected for sensor implantation so that the gradiometer can take advantage of the large spatial uniformity of the geomagnetic noise fields to reduce geomagnetic noise from calibrated ELF measurements. Figure 2 illustrates the selection of sites used from March to June 1977. As R/V Cove tows the Underwater Calibrated Source past a primary site, the triaxial superconducting magnetometer at this site measures the ELF signals from the Underwater Calibrated Source plus the ambient geomagnetic noise. Reference sites are far enough away from the source to preclude sensing the calibrated ELF signal but contain the geomagnetic noise. A difference signal, essentially the calibrated ELF signal alone, is created by subtracting a reference sensor output from the primary sensor output. This scheme, termed gradiometry, is successful because the large spatial uniformity (small gradient) of the geomagnetic noise permits a reference magnetometer to measure nearly the same geomagnetic noise as a primary magnetometer. This technique is called Long-Baseline Gradiometry because the physical separation between the primary and reference sensors is several hundred meters. Several factors influence how well the Long-Baseline Gradiometer reduces the effects of geomagnetic noise. First and foremost are the temporal and spatial polarization features of the geomagnetic noise itself. Another factor is the inhomo-
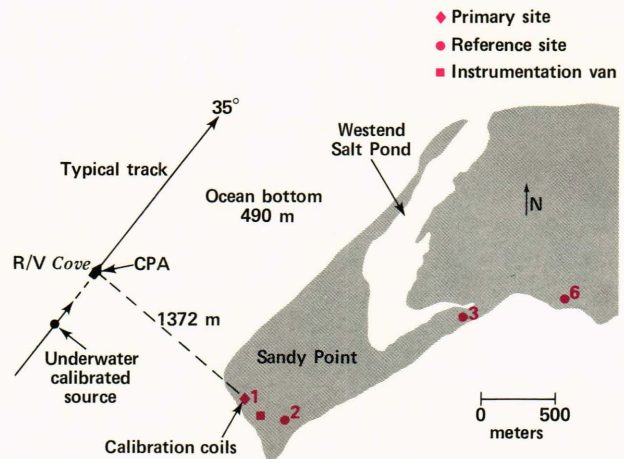

Figure 2 — The Long-Baseline Gradiometer installation at Sandy Point on the southwest tip of St. Croix, with a typical track showing closest point of approach (CPA) between the Underwater Calibrated Source and the primary sensor sites.

geneous conductivity of the ground over which the geomagnetic waves travel at the coastline and between the sensor sites. Also, at frequencies much less than 1 Hz, seismic fluctuations can differentially vibrate the magnetometers in the static earth's field, giving another contaminating noise signal.

Each magnetometer site in the gradiometer array consists of the triaxial superconducting magnetometer system previously described, which is rigidly mounted on a 1500-pound concrete slab for seismic isolation. The magnetometer-slab combination is set into a hole dug 6 feet into the ground and encased by protective nonmagnetic walls with an access lid. Electrical signals from any primary site are cabled to an instrumentation van located nearby. This van supports SQUID operating electronics, separate analog and digital data recording systems, and spectrum analysis instrumentation. SQUID operating electronics and data telemetry electronics for the reference sites are housed within separate, remote enclosures. Reference magnetometer signals are telemetered to the van by a radio-frequency link at 256.2 MHz for recording and analysis.

Underwater Detector Loops

An Underwater Detector Loop system[4] for measuring ELF signals in the ocean at depths from 15 to 100 meters has been developed and used extensively by APL. It consists of three orthogonal multiturn loops used to measure magnetic fields. The coils are placed on a platform that is suspended from a spar buoy connected to a research vessel by a flotation cable. Figure 3 indicates the nominal at-sea configuration. The detector system package is suspended via a combined electrical and mechanical cable from a spar buoy. Cable grips situated along the cable allow spar buoys to be attached at various cable stations so that the Underwater Detector Loop sensor package can be suspended at depths of 15, 30, 60, 90, 120, and
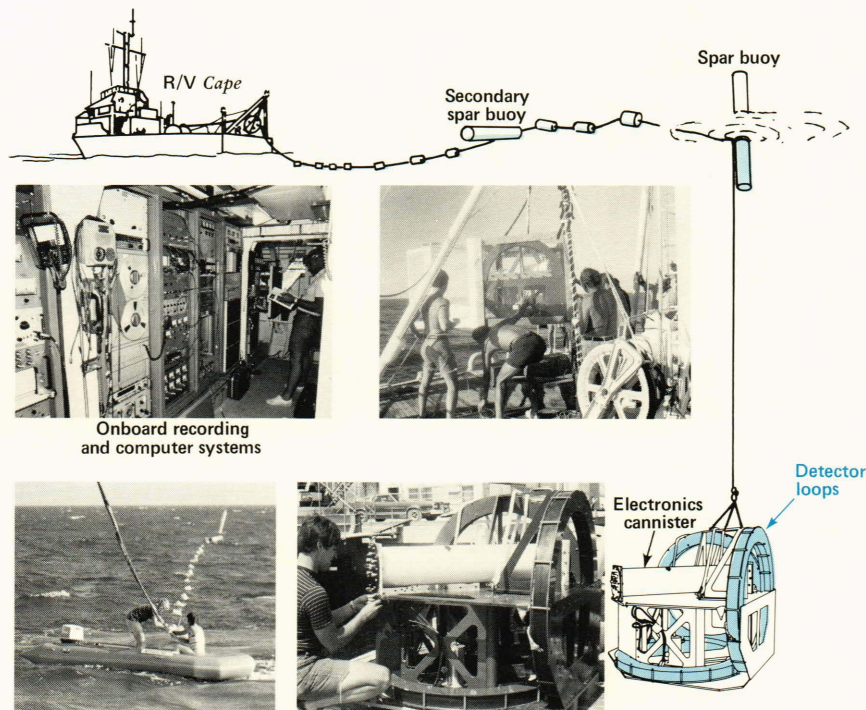
Figure 3 — Three mutually orthogonal Underwater Detector Loops suspended from a spar buoy at controlled depths and connected to the R/V *Cape* by electrical and mechanical lines.

140 meters. A quick-release hook is pulled to detach the loop sensor package suspended at one depth from a spar buoy. The sensor package drops to a second depth where it is suspended by a second spar buoy.

The platform package also contains a depth sensor, a range acoustic pinger for tracking, an acoustic hydrophone, roll and pitch sensors, accelerometers to measure platform motion, and a three-axis fluxgate magnetometer used as a compass to sense platform orientation. Support electronics on board R/V *Cape* provide data recording and real-time analysis capabilities via an analog recorder; digital recorder; minicomputer analysis systems; hard-wired spectrum analyzers; strip chart recorders; and displays for sensor package roll, pitch, and depth. A significant feature of the support electronics and computing systems is their ability to use the Underwater Detector Loop attitude sensors, particularly the fluxgate magnetometers, to correct the sensor coil signals for rotation of the sensor package.

The entire Underwater Detector Loop system (coil, platform electronics, and buoys) was designed and fabricated at APL. Electronic sensitivity tests were performed at the Naval Surface Weapons Center, and hydrodynamic stability tests were performed at the Naval Ship Research and Development Center. Each coil is 1 meter in diameter and consists of two 305-turn coils of copper wire with underwater insulation. Sensitivity of the coils is $5 \times 10^{-4} \, \gamma/\sqrt{\text{Hz}}$ over the frequency range 0.5 to 1200 Hz with a dynamic range of 90 decibels (not including data recording systems). Total harmonic distortion is less than 0.1%.

Above-Surface Propagation Measurements

A series of unique measurements was carried out near Ham's Bluff in June 1975. The major emphasis of that effort was characterizing the ELF signals from calibrated dipole sources at distances less than one free-space wavelength from the source. Because of the great range R between the source and the receiving coils on Ham's Bluff, the path for the measured radiation was primarily through the air.

Figure 4 is a typical test geometry. The Underwater Calibrated Source is towed along a heading of 65° or 245° from true north to pass about 800 to 2300 meters from the receiving coils at the closest point of approach (CPA). The ocean bottom in this region is about 2000 meters or deeper. The X component of the magnetic field is along the track or the direction of motion of the source. The Y component is cross track or is perpendicular to the X component in the horizontal plane. The positive Z component is vertically up.

The equations tested were derived by Bannister[5] and elaborated by Kraichman.[6] They describe subsurface-to-air propagation of magnetic fields from infinitesimal dipole sources.

The Ham's Bluff coastline represents an abrupt change in the conductivity of the surface over which the signals propagate. Calculations following a well-documented approach[7] show that the coastline effect on quasi-static signals is not discernible from the experimental configuration used at the Ham's Bluff station. Hence, the agreement between the received signals and the theory appears reasonable. No geo-
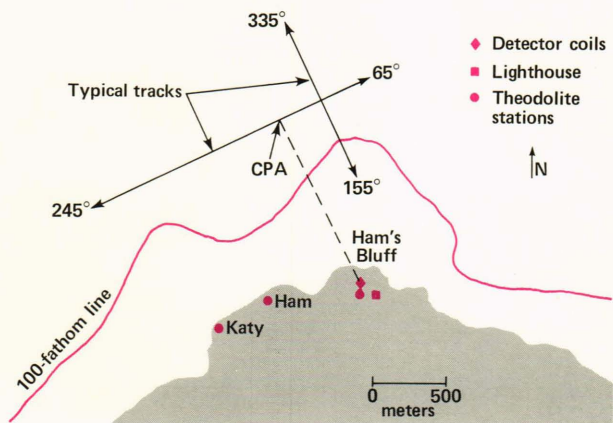
Figure 4 — Ham's Bluff measurement site on the northwest tip of St. Croix, with typical tracks for towing Underwater Calibrated Source and showing theodolite stations used for source tracking.

Figure 5 — Comparison of predicted and experimentally measured Ham's Bluff X-axis coil magnetic fields, in milligammas ($m\gamma$). The signal null near the CPA is expected from the magnetic field polarization of a dipole source.

Figure 6 — Comparison of predicted and experimentally measured Ham's Bluff Y-axis coil magnetic fields.

magnetic noise reduction techniques were employed during these measurements in 1975.

Analysis of the data requires a knowledge of the amplitude history of the signal emanating from the Underwater Calibrated Source. The history is developed by processing the analog tapes recorded at the lighthouse. The exact frequency of the signal is determined from a frequency spectrum, and a time history of the amplitude is then plotted at the selected frequency. This time history is then compared with Kraichman's equations. Figure 5 shows an example of the X component of the magnetic field with its theoretical fitted field for an 8.5-Hz run with a source strength of 150 ampere meters. The analysis bandwidth is 0.1 Hz. The source depth for this run is 32 meters, and the sensor is located approximately 90 meters above sea level. The measured field has the characteristic polarization for a horizontal electric dipole source. As expected, it nulls to the ambient noise level at the closest point of approach. The peak amplitude is about 0.27 milligamma ($m\gamma$). Figure 6 shows the Y component for the same run. It has the expected peak at the closest point of approach with an amplitude, in this case, of about 2 $m\gamma$. All of the measured field components are very noisy because of the geomagnetic and instrument background noise. The signal-to-noise ratio is low because of signal attenuation resulting from the great distance between source and receiver (about 900 meters). Nevertheless, the verification of above-surface signal reception at ranges about 1000 meters and of R^{-3} falloff is significant.

In November 1976 and again in June 1977, further above-surface tests were made off Sandy Point in St. Croix. The Long-Baseline Gradiometer was the principal receiving system, and the Underwater Calibrated Source was used again with the horizontal electric dipole as the primary dipole source. In contrast to the simple Ham's Bluff measurements, where the source was in deep water and the receiver was at 90 meters altitude, these Long-Baseline Gradiometer
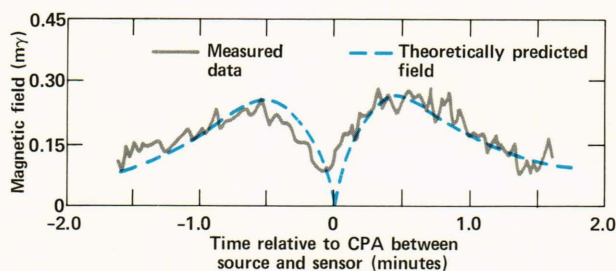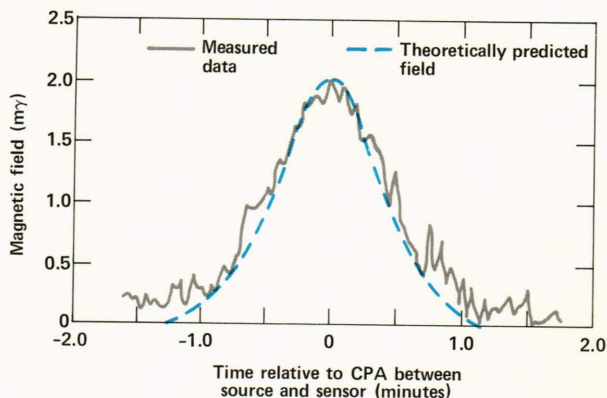
measurements, using geomagnetic noise reduction, investigated the effects of activating a dipole source in shallower water while the receiver was at sea level.

The distance between the source and the receiving magnetometer at the primary site, for a typical geometry (Fig. 2), was around 1500 meters. The ocean depth off Sandy Point at this distance is on the order of 500 meters. For distances between the source and primary site of about 600 meters, the bottom is only 45 meters deep. Geomagnetic noise in the received signals is removed in real time by simple differencing of the outputs at the primary sensor and the reference sensor. Figure 7 shows an example of a fit to the X component of the signal for a run where no such simple differencing was done. The thick solid curve is the experimental horizontal electric dipole signal. The signal amplitude of interest is determined from the signal-plus-noise spectrum by taking the square root of the sum of the squares of the three frequency bins centered about the main signal frequency. An estimate of the geomagnetic background noise is given by the thin solid curve. This noise estimate is obtained by computing the sum of the squares of 20 frequency bins adjacent to the three signal frequency bins (10 on either side). The analysis bandwidth is 0.02 Hz.

The dashed curve is the predicted field in a noise-free environment. The model assumes homogeneity in conductivity in the conducting medium. A com-
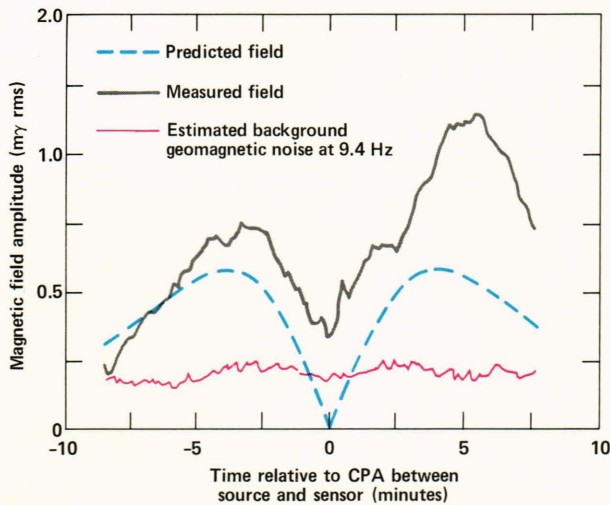
Figure 7 — Comparison of predicted and experimentally measured X-axis magnetic fields received by the Long-Baseline Gradiometer, assuming the absence of a shoreline.

Figure 8 — Comparison of predicted and experimentally measured X-axis magnetic fields received by the Long-Baseline Gradiometer, assuming the presence of a shoreline.

parison of the raw data (thick solid curve) with the theory reveals that there is asymmetry in the data that is not predicted by the model. It is conjectured that this effect is due to the asymmetry in the Sandy Point coastline. The relative orientation of the track of the Underwater Calibrated Source to the placement of the primary site causes the signal to propagate over land on the north side of the closest point of approach, whereas, on the south side of the closest point of approach, the propagation is entirely over water. Because of the lower conductivity of the land, there are fewer propagation losses on the north side; hence, a larger signal is observed.

When these results are corrected after geomagnetic noise is reduced, there is a substantial improvement in the agreement between the experimental data and the theory. This improvement is illustrated in Fig. 8; it is the same run shown in Fig. 7. Here the thick solid curve is the experimental data for the X component of the signal as seen in the gradient difference channel (i.e., the signal created by subtracting the X-reference signal from the X-primary signal). The dashed curve is the predicted field in a noise-free environment. The thin solid curve is an estimate of the background noise in this gradient difference channel. The excellent agreement between the experimental data and theory not only adds to an understanding of ELF above-surface propagation but also supports the validation of various theoretical treatments and the verification of the gradiometer techniques.

Subsurface Propagation

Another facet of ELF behavior that is not well understood because of the complex ocean structure is the subsurface-to-subsurface propagation from various dipole sources. Because the ocean is a good conductor (conductivity of about 5 mhos per meter), electromagnetic signals in the ocean undergo signifi-
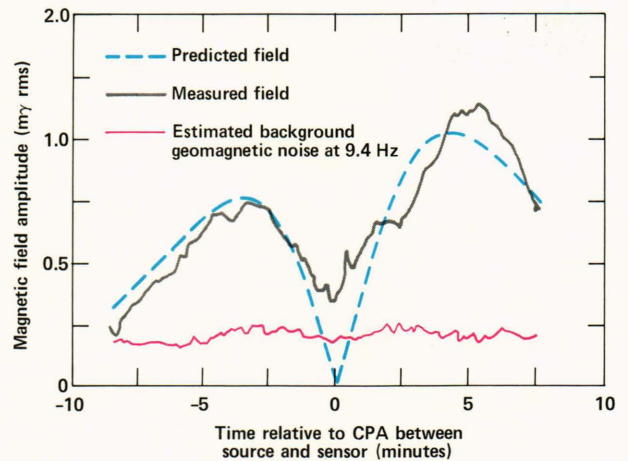
cant attenuation. Therefore, in order to measure subsurface signals from subsurface sources, measurement distances between the source and receiver are usually constrained to less than 500 meters for conventional equipment.

Because the source and detector are so close together, unlike the case in the Ham's Bluff or Sandy Point experiments, both the direct transmission path through the water and the indirect path to the surface, through the air, and then down from the surface contribute to the measured signal. This dual path propagation causes the theoretical equations that apply to be much more complicated than those used for subsurface-to-air situations. Another factor that complicates subsurface investigations is motion of the sensor system used. In the subsurface propagation experiments, the sensor is the Underwater Detector Loop, which does not have a stationary orientation as do the sensors on Ham's Bluff or the Long-Baseline Gradiometer. The sensor system is free to rotate in the water, making it necessary to determine its orientation as a function of time relative to a stationary coordinate system.

Several measurements using the Underwater Calibrated Source as the signal generator have been performed off Ft. Lauderdale and St. Croix since 1976. The equations that are used in fitting the experimental data were derived by Weaver.[8] They differ significantly from the subsurface-to-air expressions derived by Kraichman, which have a simple R^{-3} dependence. Weaver's expressions for the magnetic field of a horizontal electric dipole have complex expressions wherein the R dependence is contained in Bessel functions and their derivatives in addition to terms that have a geometric and exponential dependence on R.

Throughout each test, conductivity, temperature, and depth profiles were taken to provide conductivity information used in the theoretical modeling. Weaver's equations were derived to account for con-

ductivity stratification in the ocean that, typically, is not considered. The Weaver formulation has two layers of differing conductivity in the conducting medium bounded by a semi-infinite space of zero conductivity. A simplified model using a single conductivity throughout the conducting medium is used here to compare with the data.

Several criteria are taken into consideration in judging the success of these comparisons between theory and experiment. Correct signal polarization for a horizontal electric dipole and the ability to infer the source strength within the limits of experimental accuracy are of prime concern. The data demonstrate again that the signal from the horizontal electric dipole has the expected polarization for its X and Y components.

The ratios of the inferred source strength to the actual source strength for the horizontal and vertical components were statistically analyzed with least-squares techniques.[9] The results (Table 1) show good agreement between the predicted and measured fields. The standard deviation is found to agree well with the expected uncertainty of 20%. The expected uncertainty was obtained from an analysis of the sensitivity of the theory to the various input parameters such as depth, source-sensor separation, and source current.

Table 1

INFERRED SOURCE STRENGTH RESULTS FOR A HORIZONTAL ELECTRIC DIPOLE SOURCE USING THE UNDERWATER DETECTOR LOOP SENSOR PACKAGE

	Ratio of Inferred to Actual Source Strength		
	Expected Value	Measured Value	Standard Deviation
Horizontal component	1.0	1.03 (65)*	0.22
Vertical component	1.0	1.06 (62)*	0.20

*Number of test runs.

Noise Reduction Techniques

There are two major sources of geomagnetic noise in the ELF band from 0.5 to 1000 Hz: geomagnetic micropulsations and lightning. Below 5 Hz the micropulsations are caused by disturbances in the earth's magnetosphere. Above 5 Hz, lightning noise dominates the spectrum. The so-called Schumann resonances[10] are the most interesting result of lightning noise and are predominant in the 5 to 50 Hz range. Figure 9 illustrates a typical geomagnetic noise spectrum measured with 0.01-Hz bandwidth.

Since geomagnetic noise is the most contaminating feature in ELF measurements, background geomagnetic noise surveys are routinely conducted as a distinct phase of ELF tests in the ocean environment. Both the Ham's Bluff receiving coils and the gradiometer array were used to make background noise measurements in an attempt to determine the spectral polarization content and statistical properties of geomagnetic noise as well as to test various noise reduction techniques.

Various methods of signal processing for reducing geomagnetic noise are used on the gradiometer data.[11] Each method exhibits some utility, and some show more promise than others. The first method employed, simple differencing, merely subtracts the output of each axis of the reference magnetometer from the output of the corresponding axis of the primary magnetometer. Results from the placement of the reference magnetometer at different sites show that the ability to cancel noise decreases with distance and changes in geology and subsequent correlation between magnetometer sites. Other signal processing techniques are being applied to these gradiometer data at APL. Algorithms that apply variations of the classic Wiener filter are used to maximize noise reduction by subtracting from a primary sensor axis either a fixed linear combination of multiple axis reference channels (i.e., Wiener-Hopf filter[12]) or a continuously updated weighted output of several reference axes (i.e., adaptive filtering[13]). Thus far, these techniques yield several decibels more noise reduction than does simple differencing. Comparison of signal processing techniques on the geomagnetic noise data is giving useful information about geomagnetic noise, such as stationarity and cross-spectral characteristics for the Cartesian components of the noise fields at different locations.

CONCLUDING REMARKS

The investigation of ELF electromagnetic phenomena in the ocean environment has led to major contri-
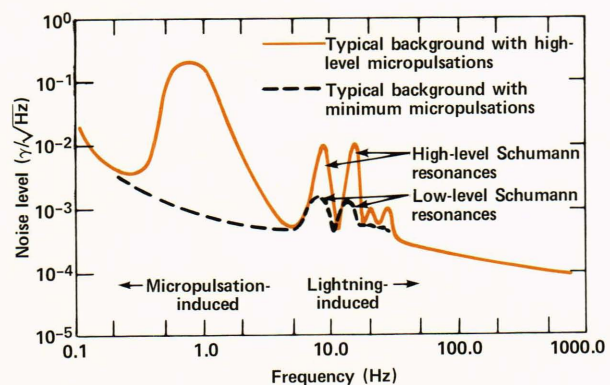
Figure 9 — Typical geomagnetic noise spectrum with 0.01-hertz bandwidth showing lightning-induced Schumann resonances and micropulsations induced by fluctuations in the magnetosphere. Micropulsations dominate the spectrum below 5 hertz. Noise reduction techniques are used to remove this natural background noise from magnetic propagation data.

butions in the areas of propagation validation, geomagnetic noise characterization, signal processing, and electromagnetic ocean engineering. Unique experimental measurements and subsequent analysis have resulted in the verification of existing theory for ELF subsurface-to-subsurface and subsurface-to-air propagation. Geomagnetic noise measurements have been used in conjunction with signal processing techniques to obtain several decibels of noise reduction in above-surface measurements. The state of the art in the design of underwater electromagnetic systems has been advanced by APL's efforts in this program. Much has been learned concerning the deployment of vector electromagnetic sensors and the compensation of resulting motion noise.

Future efforts in the direction indicated here should enable simultaneous worldwide measurements of geomagnetic noise down to 10^{-4} $\gamma/\sqrt{Hz}$ levels and provide deeper insight into subsurface-to-subsurface alternating electromagnetic field propagation. Application of the high technology of superconducting systems, towed body design, and at-sea computer analysis systems should lead to further development of pacesetting ocean electromagnetic instrumentation. The integration of the results from ELF electromagnetic investigations, both past and future, continues to foster progress in many aspects of ocean technology.

REFERENCES

[1] J. R. Wait, "Historical Background and Introduction to the Special Issue on ELF Communications," *IEEE Trans. Commun.* **COMM-22**, 353-355 (1974).

[2] F. S. Billig, C. J. Gundersdorf, and L. J. Crawford, "Oceanographic Research at APL," *APL Tech. Dig.* **16** No. 1 (1977).

[3] B. E. Tossman, D. L. Thayer, and W. A. Swartz, "An Underwater Towed Electromagnetic Source for Geophysical Exploration," *IEEE Trans. Ocean Eng.* **OE-4**, 84-89 (1979).

[4] D. L. Thayer, L. Scheer, and B. E. Tossman, "A Triaxial Coil Receiver System for the Study of Subsurface Electromagnetic Propagation," *IEEE Trans. Ocean Eng.* **OE-7**, No. 2 (1982).

[5] P. R. Bannister, "The Quasi-Near Fields of Dipole Antennas," *IEEE Trans. Antennas Propag.* **AP-15**, 618-626 (1967).

[6] M. B. Kraichman, *Handbook of Electromagnetic Propagation in Conducting Media,* NAVMAT (1970).

[7] J. R. Wait, "Recent Analytical Investigations of Electromagnetic Ground Wave Propagation Over Inhomogeneous Earth Models," *Proc. IEEE* **62**, 1061-1072 (1974).

[8] J. T. Weaver, "The Quasi-Static Field of an Electric Dipole Embedded in a Two-Layer Conducting Half Space," *Can. J. Phys.* **45**, 1981-2002 (1967).

[9] J. A. Giannini and D. L. Thayer, "Extremely Low Frequency (ELF) Quasi-Static Propagation Measurements from a Calibrated Electric Field Source in the Ocean," *IEEE Trans. Antennas Propag.* (in press).

[10] J. Galejs, "Frequency Variations of Schumann Resonances," *J. Geophys. Res.* **75**, 3237-3251 (1970).

[11] J. D. Cornwell, *Survey of Several Advanced Signal Processing Techniques Applicable to ELFE, Science Applications, Inc.,* JHU/APL POR 3755 (Oct 1977).

[12] J. D. Cornwell, *Theoretical Limits to the Performance of ELFE Noise Cancellers, Science Applications, Inc.,* JHU/APL STD-R-026 (Apr 1978).

[13] B. Widrow *et al.,* "Adaptive Noise Cancelling: Principles and Applications," *Proc. IEEE* **63**, 1692-1716 (1975).